Title
Peculiarly pleasant weather for US maize.

Journal
Proceedings of the National Academy of Sciences of the United States of America, 115(47)

ISSN
0027-8424

Authors
Butler, Ethan E
Mueller, Nathaniel D
Huybers, Peter

Publication Date
2018-11-01

DOI
10.1073/pnas.1808035115

Peer reviewed

Peculiarly pleasant weather for US maize

Ethan E. Butler[a,1], Nathaniel D. Mueller[b], and Peter Huybers[c]

[a]Department of Forest Resources, University of Minnesota, St. Paul, MN 55108; [b]Department of Earth System Science, University of California, Irvine, CA 92697; and [c]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA 02138

Edited by Inez Fung, University of California, Berkeley, CA, and approved October 4, 2018 (received for review May 9, 2018)

Continuation of historical trends in crop yield are critical to meeting the demands of a growing and more affluent world population. Climate change may compromise our ability to meet these demands, but estimates vary widely, highlighting the importance of understanding historical interactions between yield and climate trends. The relationship between temperature and yield is nuanced, involving differential yield outcomes to warm (9 – 29 °C) and hot (> 29 °C) temperatures and differing sensitivity across growth phases. Here, we use a crop model that resolves temperature responses according to magnitude and growth phase to show that US maize has benefited from weather shifts since 1981. Improvements are related to lengthening of the growing season and cooling of the hottest temperatures. Furthermore, current farmer cropping schedules are more beneficial in the climate of the last decade than they would have been in earlier decades, indicating statistically significant adaptation to a changing climate of 13 kg·ha^{-1}·decade^{-1}. All together, the better weather experienced by US maize accounts for 28% of the yield trends since 1981. Sustaining positive trends in yield depends on whether improvements in agricultural climate continue and the degree to which farmers adapt to future climates.

agriculture | maize | climate | trends | adaptation

Increased agricultural production over the 20th century is a celebrated achievement of modern science (1). Continuation of these trends is essential to meeting future food and nutritional demands (2, 3), although our ability to do so may be compromised by climate change (4–6). To better understand how climate change will interact with future trends in crop yield, it is important to establish both how climate influenced historical crop yields and how farmers have responded to these changes. To explore these issues, we focus on maize, an important food, feed, and fuel crop in the US Midwest that is both highly productive and strongly influenced by temperature (7, 8).

Previous studies of US maize found that warming suppressed yield trends in Wisconsin (9) and that short-term cooling increased yield trends across the country (10, 11). These earlier studies did not, however, distinguish between moderate temperatures that are beneficial and hot temperatures that are damaging (7, 12), instead using growing-season temperature averages as explanatory variables. This distinction is especially relevant for the US Corn Belt because daily minimum temperatures have risen nearly ubiquitously (13, 14), whereas the hottest growing-season temperatures have cooled by ∼1–2 °C over the last century (13, 15).

Recent work indicates that increasing yield trends are linked to earlier planting and longer maturing varieties (16–19). However, studies have found no evidence of US agricultural adaptation to historical changes in climate (7, 20). The combination of warming and absence of adaptation leads to alarming scenarios regarding climate-induced reductions in yield (7). However, the presumption of no adaptation seems at odds with the ingenuity of farmers, a characterization that is supported by evidence of regional adaptation to climate (8, 21) and patterns of insurance coverage that indicate careful apportionment of weather-related risks (22).

Yield Trends from Changes in Climate and Crop Timing

Here, we use a recently developed statistical growth model (21) to analyze how changes in temperature distributions and crop phenology influence maize yield. Yield is modeled according to accumulated growing degree days (GDDs) and killing degree days (KDDs), the latter of which measure exposure to damagingly–high temperatures (8, 20, 23). To account for the fact that temperature sensitivity varies greatly over the course of crop development (24, 25), yield sensitivity to GDDs and KDDs varies across vegetative, early-, and late-grain-filling growth phases (Fig. 1 and *SI Appendix*, Fig. S1). The model accounts for 72% of the interannual variance in maize yield in the median county (*SI Appendix*, Fig. S2).

It is useful to distinguish between the influence of climate trends and timing trends associated with planting and crop development. We first isolate influences associated with climate trends by fixing planting and growth-phase dates to their average values between 1981 and 2017. Averaging across the Midwest, GDDs increase during every phase with a total increase of 14 °C days per decade (*SI Appendix*, Fig. S3). By contrast, KDDs decreased during every growth phase, for a net change of −10 °C days per decade (*SI Appendix*, Fig. S4). These remarkable improvements in weather combine to increase yields by 0.2 tonnes/ha per decade (95% CI 0–0.5; Figs. 2 *A* and *B* and 3).

Increasing GDDs is consistent with general warming driven by increasing greenhouse gases, whereas suppression of the high-temperature extremes that produce KDDs appears to be a fortuitous by-product of more productive row-crop agriculture and corresponding increases in evapotranspiration (15, 26). Strong associations between increasing summer crop productivity and cooler extreme temperatures are found in the Midwest (15) as well as other major cropping regions (27–29). Increased irrigation also cools surface air temperature (30, 31), but we

Significance

Over the course of the 20th century, US maize yields have improved by more than a factor of five. Whereas this trend is often attributed exclusively to technological improvements, here, we also identify contributions from improved temperatures during the growing season. More than one-quarter of the increase in crop yield since 1981 is estimated to result from trends toward overall warmer conditions, but with cooling of the hottest growing-season temperatures, and from adjustments in crop timing toward earlier planting and longer maturation varieties.

Author contributions: E.E.B., N.D.M., and P.H. designed research; E.E.B. performed research; E.E.B. analyzed data; and E.E.B., N.D.M., and P.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: Code to download and organize the data as well as perform analyses and produce the figures are available from https://github.com/eebutler/us_maize_trends.

[1]To whom correspondence should be addressed. Email: eebutler@umn.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1808035115/-/DCSupplemental.

Published online November 5, 2018.

SUSTAINABILITY SCIENCE

focus on rainfed counties because only ∼20% of counties in the Midwest have at least 10% of their harvested acreage equipped for irrigation.

The effects of changes in the timing of the growing season is explored by specifying a fixed seasonal climatology. Timing is controlled by planting date and the temperature-modulated time needed by a cultivar to develop, also referred to as the maturity rating (32). Planting dates have shifted by almost 3 d earlier per decade. This shift has been attributed to hardier hybrid stocks, improved planting equipment, and chemical seed coatings (16, 33, 34), but also coincides with early-season warming across most of the Midwest (*SI Appendix*, Fig. S3). Earlier planting has been accompanied by increases in maturity rating such that harvest dates have remained relatively constant, with 90% of the additional duration of the growing season accounted for by a longer grain-filling phase (*SI Appendix*, Fig. S7). Prior work has also documented the yield benefits of earlier planting (16, 17) and longer season varieties (18, 19), although without differentiating the influence of the distinct trends in moderate and hot temperatures.

Trends toward earlier planting change GDDs during the vegetative phase by $-16\,^{\circ}$C days per decade, but this decrease is more than counterbalanced by an increase of $26\,^{\circ}$C days per decade during grain filling on account of this stage lengthening and shifting into a warmer part of the seasonal cycle. This repartitioning of GDDs from the vegetative to grain-filling phases is clearly beneficial on the whole (Fig. 2*C*) because yield is >10 times more sensitive to GDDs during grain filling (*SI Appendix*, Table S1). The longer growing season in northern counties only mildly increases exposure to damaging temperatures because KDDs are uncommon (Fig. 2*D* and *SI Appendix*, Fig. S4). In more southern counties, KDDs accrue more regularly, and early grain filling incurs the greatest additional exposure on account of both lengthening and shifting into a hotter part of the seasonal cycle (*SI Appendix*, Figs. S5 and S7).

Weather-related increases in yield are unevenly distributed across the Midwest with a northwest gradient toward increasing yields (Fig. 2 *E* and *F*). States that benefit the most experience greater GDDs, particularly during the critical late grain-filling stage, while also enjoying declining KDDs. Kentucky, by contrast, has experienced a decline in the duration of late grain filling by nearly 2.5 d per decade, accounting for a reduction in GDDs and a drag on its yield trend of -0.2 tonnes/ha per decade (Fig. 2*C*). On average across the Midwest, climate and timing trends together account for a yield trend of 0.36 tonnes/ha per decade, or 28% of the total 1.28 tonnes/ha per decade trend across the Midwest since 1981 (Fig. 3).

Adaptation to Climate Change

To this point, our analysis has treated changes in climate and farmer-controlled adjustments independently, but their union is needed to assess adaptation to climate change. That is, to constitute adaptation to climate change, adjustments should give higher yields under recent climate conditions than gains obtainable under earlier climate conditions (35). We test whether changes in planting schedule constitute adaptation to climate change by comparing expected maize production over 1981–2017 when fixing developmental timing to the 1981–1990 average versus the 2008–2017 average (Fig. 1). The difference in expected yield, δY_t, gives a time series whose mean indicates adaptation to climatology and whose trend indicates adaptation to climate change (Fig. 4).

Adaptation to seasonal climatology gives a δY_t of 0.4 tonnes/ha for the average county. This difference is highly statistically significant ($P < 0.01$, one-sided test), consistent with contemporary longer-maturing cultivars being successful adaptations to the climatological seasonal cycle. The only year in the last decade with notable yield loss from the recent development schedule is 2012, when extreme heat occurred during early grain filling, the most sensitive period of development. Using the 1980s development schedule, the 2012 drought and heatwave would have predated this sensitive period and been less damaging in some counties.

Beyond shifts in the mean, a positive trend in δY_t indicates that changes in the timing of crop development are more beneficial under recent climate and, thus, represent adaptation to changes in climate. A least-squares fit to all counties gives a trend of 13 kg/ha per decade (Fig. 4) that is also highly significant ($P < 0.01$, one-sided), but varies considerably from state to state (*SI Appendix*, Fig. S8). Note that, although climate adaptation is typically considered in the context of mitigating damages (35), in the present context, adaptation serves to accentuate trends toward increased yield. Along similar lines, a process model analysis of maize growth in China (36) also found that a warming trend allowed for longer growing seasons and that selection of appropriate cultivars lead to improved yields, even

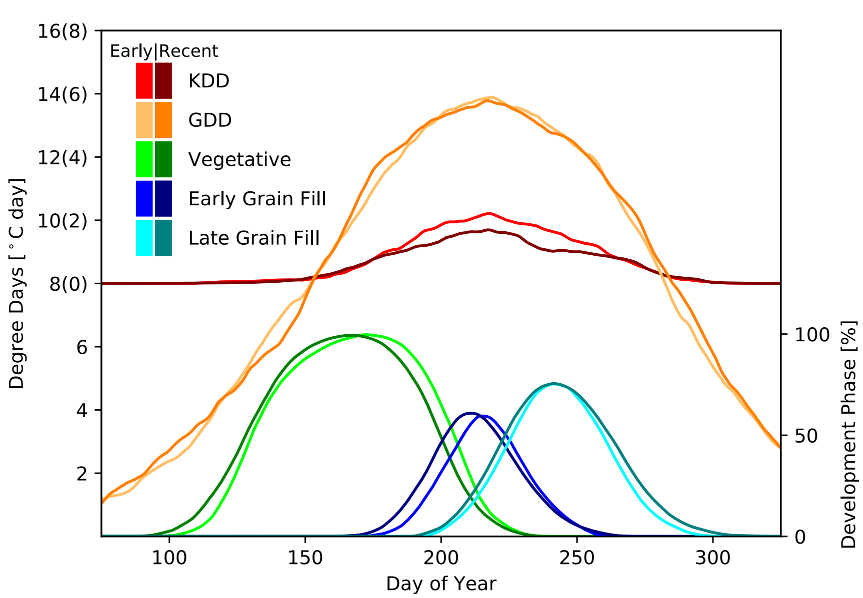

Fig. 1. Regional climate and development. Midwestern US maize develops through vegetative (green), early grain-filling (blue), and late grain-filling (cyan) growth phases beginning as early as April and ending as late as October. Also shown is the climatology of GDDs (orange) and KDDs (red) over the growing season after smoothing with a 30-d window for purposes of clarity. KDDs are shifted upward such that 0 KDDs and 8 GDDs are level. Light shading indicates the earliest decade in the analysis (1981–1990) and dark the latest (2008–2017), where more recent growing seasons begin earlier and end later, have lower KDD exposure, and have higher GDD exposure related to longer maturation.

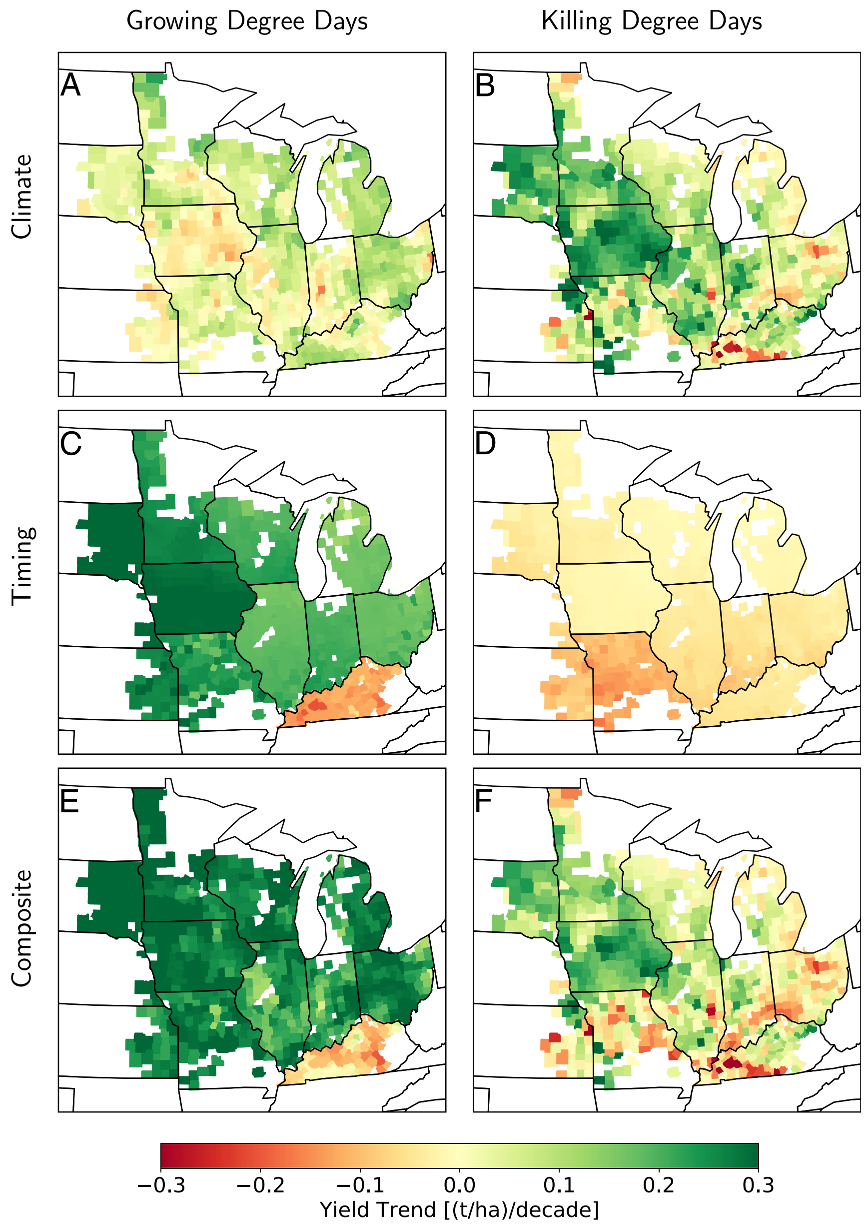

Fig. 2. Spatial components of the yield trend. (*A*–*D*) Yield trends are broken into those attributable to climate from GDDs (*A*) and KDDs (*B*) and those attributable to timing from GDDs (*C*) and KDDs (*D*). (*E* and *F*) The combined influence on yield trends from GDDs (*E*) and KDDs (*F*) is also shown. Trends are in tonnes per hectare per decade and are computed between 1981 and 2017.

as warming trends led to greater exposure to damage from high temperatures.

The form of adaptation identified here is associated with earlier planting and selecting cultivars that take advantage of a longer growing season. As noted, this earlier planting is facilitated by technological advances (16, 33, 34), but warming of average daily-minimum temperatures in the Midwest by $0.1\,^{\circ}$C/decade in April and May have almost certainly aided this shift. Furthermore, there is strong evidence of phenological indicators in unmanaged ecosystems shifting earlier (37–39). At one midwestern site, an average shift of -1.2 d per decade is documented for a range of species and phenophases (40). Maize trends exceed those of the unmanaged landscape by more than a factor of two, illustrating the dual role of management and climate in setting the developmental timing of agro-ecosystems.

Discussion and Conclusions

The combined changes that farmers, crop breeders, and agronomists have realized for US maize production have better aligned the timing of crop growth with historical seasonal conditions. This result is consistent with those from crop models used to explore the implication of longer maturing varieties in both the United States (18) and China (36). At the same time, improvements in Midwest weather have led to more GDDs and fewer KDDs. The combined effects of changes in climate and crop timing lead to further yield increases that constitute a modest but statistically significant adaptation to climate change. Together, these improvements represent more than a quarter of Midwestern trends in maize yield since 1981. This estimate is comparable to a recent analysis of maize phenology using satellite data (19) that attributes 23% of the maize yield trend from 2000–2015 to lengthening grain filling.

Recognition that historical improvements in yield partly depend on improvements in climate suggests that sustaining positive yield trends depends more on climate than previously appreciated. Purely technological improvements are smaller than previously assumed, insomuch as historical temperature trends are responsible for improved yields, as opposed to temperature trends being essentially inconsequential (11) or reducing yields

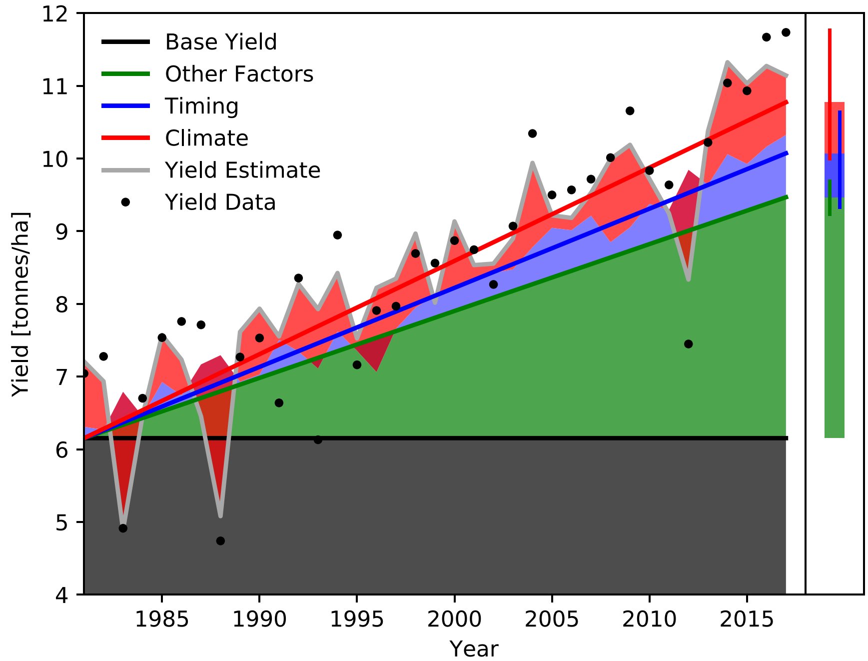

Fig. 3. Components of the yield trend. Observed yields averaged over the US Midwest between 1981 and 2017 (black dots) along with our temperature-driven model estimate (gray line). The yield trend is broken into components attributable to an improvement in climate [red, 0.2 (0–0.5) t/ha, best estimate and 95% CIs, timing adjustments [blue, 0.2 (0–0.3) t/ha per decade], and other factors improving yields [green, 0.9 (0.9–1.0) t/ha per decade]. Also shown is the baseline yield referenced to 1981 (6.2 t/ha). The stacked bar on the far right side shows the total contribution, as of 2017, from each of these components and the associated 95% CIs.

(9). However, the benefits of longer grain filling may also be harder to sustain in a warmer climate (19, 21). Furthermore, there is no assurance that beneficial climate trends will persist. Cooling of extreme temperatures appears an unintended cobenefit of greater landscape productivity (15, 26, 29) and may cease when traditional methods of improving crop productivity are exhausted. If yield trends slow when nearing intrinsic yield potentials (41–43), associated cooling trends may also slow. Rising CO_2 levels may also limit requirements for stomatal opening (44) and thereby limit cooling by transpiration. CO_2 fertilization could independently benefit yields, although its effect is more limited for C4 crops like maize (45), and mechanistic models show widely varying sensitivities (46). Note that CO_2 fertilization and other environmental factors such as ozone exposure (47) and global dimming (48) are implicitly accounted for within the "other factors" term in our analysis (Fig. 3).

Whether historical patterns of adaptation will prove successful under future climate is also unclear. If droughts like those in 1988 and 2012 grow more frequent or intense, they could overwhelm the benefits of planting longer-maturing varieties. Relatedly, earlier planting moves more sensitive phases of maize development into a hotter portion of the seasonal cycle, and if historical cooling of extremes reverses, timing adjustments could prove maladaptive. Farmers could be driven toward growing faster-maturing varieties that entail less exposure to extremes at the cost of lower yield potential. Although the greater vulnerability to weather implied by these findings is concerning, evidence that farmers have taken advantage of historical changes in climate to optimize yields supports the notion of continued adaptation to future changes in climate.

Materials and Methods

Data. We focus on states in the US Corn Belt: Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, Ohio, South Dakota, and Wisconsin. State-level crop development data and county-level yields from the US Department of Agriculture's National Agriculture Statistics Service (USDA/NASS) (49) from 1981 to 2017 are available for all of these states.

Weather data are from 342 US Historical Climatology Network weather stations from the Global Historical Climatology Network (50) and interpolated with a Delaunay Triangulation (51) to the center of each county to approximate the daily weather experienced by the crop. Reanalysis products are not used to calculate temperature trends because, whereas these may be adequate for some metrics, summertime extreme temperatures are generally poorly represented (52).

Counties with >10% of their harvested area irrigated according to the four 1997–2012 censuses of agriculture are removed from the analysis, as they are known to be significantly less sensitive to temperature, as are peripheral counties in the Upper Peninsula of Michigan and those west of 100°W longitude (8, 53). Remaining counties with <25 y of data are omitted from the analysis. Of 1,111 counties and 37,506 county-years in these 12 states, 775 counties and 27,806 county-years of data meet all requirements.

Code to download and organize the data as well as perform analyses and produce the figures are available from https://github.com/eebutler/us_maize_trends.

Models. GDDs are typically used as a measure of the thermal time required for a specific cultivar to develop, but in this aggregate analysis, there are many maturity classes within any given state on any given year, and yearly GDDs help determine which of those cultivars are most successful (54). This approach is in keeping with previous aggregate statistical studies (8, 20, 23, 55, 56). The daily heat unit, GDD_d, is defined on each day, d, using the representation of (32),

$$GDD_d = \frac{T^*_{\min,d} + T^*_{\max,d}}{2} - T_{\text{low}}, \quad [1]$$

where,

$$T^*_{\max,d} = \begin{cases} T_{\max,d} & \text{if} \quad T_{\text{low}} < T_{\max,d} < T_{\text{high}}, \\ T_{\text{low}} & \text{if} \quad T_{\max,d} \le T_{\text{low}}, \\ T_{\text{high}} & \text{if} \quad T_{\max,d} \ge T_{\text{high}}. \end{cases} \quad [2]$$

$T^*_{\min,d}$ is defined by using the same low and high bounds of $T_{\text{low}} = 9\,^\circ\text{C}$ and $T_{\text{high}} = 29\,^\circ\text{C}$.

Damaging heat units, KDDs, reduce yields through pathways such as desiccation and accelerated development and are quantified as,

$$KDD_d = \begin{cases} T_{\max} - T_{\text{high}}, & \text{if} \quad T_{\max} > T_{\text{high}}, \\ 0, & \text{if} \quad T_{\max} \le T_{\text{high}}. \end{cases} \quad [3]$$

Development data are available for six distinct growing stages: planting, silking, doughing, dented, mature, and harvested. These are combined into three growing phases. Planting to silking is the vegetative phase, silking to doughing is the early grain-filling phase, and doughing to mature is the late grain-filling phase. The drydown phase, which was included in ref. 21, is omitted as being less important and to reduce overall degrees of freedom. Stages are presented as weekly percentages of crop development in the

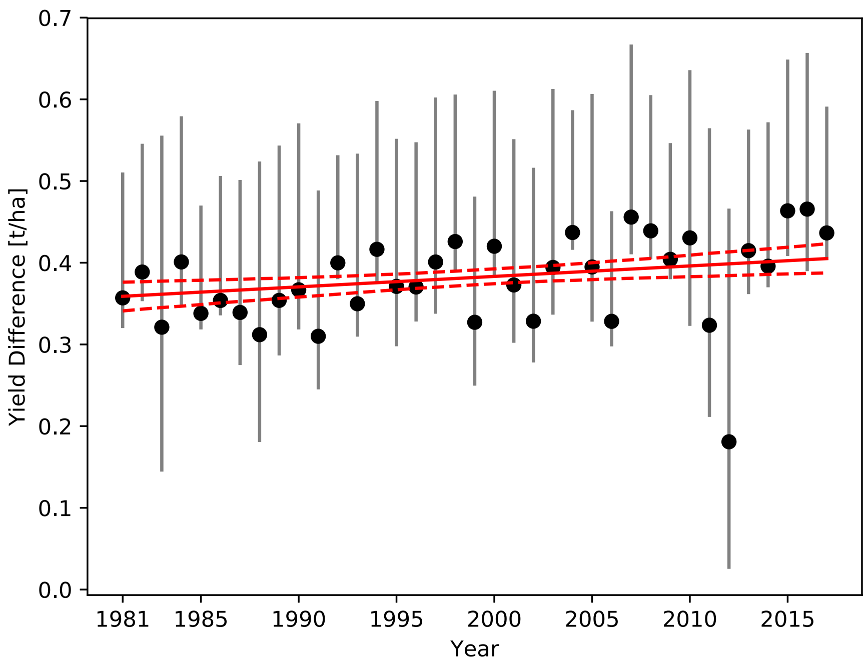

Fig. 4. Evidence of adaptation to climate change. Yield differences are computed for each county by subtracting yields modeled using the average 1981–1990 timing of development phases and subtracting those yields modeled using the 2008–2017 development timing. Although there are variations across counties (gray whiskers show the interquartile spread), averages of the yield differences (black dots) show a clear positive mean and trend. The positive mean primarily reflects the fact that a longer growing season is beneficial. The positive trend of 13 kg/ha per decade (red line, from a least-squares fit) is significant at the 95% confidence level (4–21 kg/ha per decade CI, red dashed lines) and indicates significant farmer adaptation to climate change. The 95% CI is constructed from bootstrapping upon cluster-years. Bootstrapping accounts for outliers in the sample distribution, such as those that result from the 2012 drought, and clustering accounts for spatial autocorrelation (*Materials and Methods*).

USDA/NASS database, and these are linearly interpolated to daily values and linearly extrapolated to 0 and 100% bounds.

GDDs are calculated for each county, *c*, and development phase, *p*, according to $\mathrm{GDD}_{p,c} = \sum_d P_{p,c,d}\mathrm{GDD}_{c,d}$, where the sum is over the days, *d*, in the growing season. *P* is the fraction of crop in development phase *p*. These data are only available at the state level, and values for all counties within a state are assumed identical. $\mathrm{KDD}_{p,c}$ is calculated analogously.

Development-phase-weighted GDD and KDD variables are combined into a panel model of yield,

$$Y_{y,c} = \beta_{0,c} + \beta_1 y + \sum_{p=1}^{3}\left(\beta_{2,p}\mathrm{GDD}'_{y,c,p} + \beta_{3,p}\mathrm{KDD}'_{y,c,p}\right) + \epsilon_{y,c}. \qquad [4]$$

Yield is predicted in metric tons/ha for each year, *y*, and county, *c*. Values for β are defined across the entire domain except for $\beta_{0,c}$, which represents mean county-level yield. The β_1 term represents the temporal yield trend that is distinct from those due to trends in GDD and KDD. Yield sensitivities to GDD and KDD vary according to growth phase. Mean values of $\mathrm{GDD}_{y,c}$ and $\mathrm{KDD}_{y,c}$ are removed, as indicated by primes. See *SI Appendix*, Table S1 for estimated sensitivities.

The influence of GDD and KDD trends on yields is obtained by multiplying by the respective sensitivities and summing,

$$\overrightarrow{Y^{GK}}_c = \sum_{p=1}^{3} \overrightarrow{\mathrm{GDD}'}_{p,c}\beta_{2,p,c} + \overrightarrow{\mathrm{KDD}'}_{p,c}\beta_{3,p,c}. \qquad [5]$$

Time trends in GDDs and KDDs are calculated with an ordinary least-squares fit and are shown in *Top* of *SI Appendix*, Figs. S3 and S4. Bootstrap uncertainties on trends in GDDs and KDDs are calculated by sampling pairs of GDDs and KDDs to preserve covariance between these fields.

A version of Eq. **4** including terms relating to linear and squared seasonal precipitation values was also explored (*SI Appendix*, Table S4), but this explains only 1% more of yield variance and does not qualitatively change the interpretation of yield trends.

In addition to the yield trends calculated using Eq. **5**, two restricted scenarios are considered. First, historically variable development phases are specified but with a fixed seasonal climate of daily GDD and KDD. Second, growth phases are fixed to begin and end on the same day every year according to mean development dates, whereas weather varies according to historical changes.

For purposes of attribution of trends in these restricted scenarios, it is useful to distinguish between farmer-controlled planting decisions and those resulting from exposure to different temperature regimes. The fact that exposure to KDDs variously influences the duration of growth phases was documented earlier (21), and here we estimate the sensitivity of the duration of growth phase, *p*, to KDDs by regressing variability reported for a given state across years according to,

$$D_{p,y} = \alpha_{0,p} + \alpha_{1,p}\overline{\mathrm{KDD}}_{p,y} + \epsilon, \qquad [6]$$

where $D_{p,y}$ indicates the duration of a growing phase, $\alpha_{0,p}$ is an intercept, and $\alpha_{1,p}$ indicates sensitivity of duration to KDDs for each growth phase. $\overline{\mathrm{KDD}}_{p,y}$ is the average KDDs across counties and days within a given state according to growth phase and year. The anomalous duration attributable to KDDs is then defined as,

$$D'_{p,y} = \alpha_{1,d}\overline{\mathrm{KDD}}_{p,y}. \qquad [7]$$

Exposure to KDDs generally leads to shorter growing phases across the Corn Belt and, given overall reductions in KDDs, is associated with an average lengthening of grain filling by 0.4 d/decade, or 15% of the observed trend.

The anomalous KDDs experienced as a result of changes in growing-season length are estimated as,

$$\mathrm{KDD}^*_{p,y} = D'_{p,y}\overline{\mathrm{KDD}}_{p,y}. \qquad [8]$$

KDD* are subtracted from the farmer-controlled timing attribution and added to the climate-controlled attribution. The lengthening of the growing season is associated with a small trend of 0.4 KDDs per decade. Anomalies in phase duration are also used to calculate $\mathrm{GDD}^*_{p,y}$ using the same relationships found in Eq. **8**. Lengthening of grain filling is estimated to contribute 5 GDDs per decade. Yield effects of these anomalous KDDs and GDDs are modest, but are included for purposes of completeness.

There is some concern that such a simple model may have omitted variables driving the relationship between GDD, KDD, and yield. However, there are three lines of evidence indicating that the model is well posed. First, a cross-validation procedure in which 20% of the county years are omitted from the training dataset results in a model R^2 of 0.78 for the predictive set that is comparable to that for the training set, 0.79 (*SI Appendix*, Fig. S2). Second, the relationship between growth duration and temperature is controlled for and would not alter our conclusions regardless (Eq. **6**–**8**). Finally, estimated yield sensitivity to GDDs and KDDs (*SI Appendix*, Table S1) are consistent with physiological expectations, including that sensitivities are low during the vegetative phase and highest to KDDs during early grain filling (21, 24, 25).

Despite overall reliable predictions, our model underestimates yield loss during the 2012 drought (Fig. 3). This underestimate can be understood in that the 2012 drought coincided with the most sensitive phases of crop development, silking and tasseling, whereas our model groups these sensitive phenological periods into a single, longer early grain-filling phase.

Lack of explicitly resolving silking and tasseling may therefore account for underestimation of damage. Further, despite covariance between drought and extreme heat (57), our model does not explicitly resolve crop stress from low soil moisture.

Bootstrap CIs are constructed to assess the uncertainty associated with each of the statistical models by using 1,000 samples that account for contributions from errors in trend estimates, sensitivity parameters, as well as D' and therefore KDD* and GDD* terms. County-years are used as the unit of replication. To be more conservative with respect to regional estimates, we also explore the implication of spatial autocorrelation using a K-means clustering algorithm on longitude, latitude, and mean yield to generate 108 clusters. This number of clusters reflects numbers of agricultural districts that average nine per state (*SI Appendix*, Fig. S9). The 95% CI of the adaptation trend is 13–20 kg/ha per decade when resampling on county-years, 4–21 kg/ha per decade when resampling on spatial clusters and years, and −3 to 32 when resampling on yearly regional averages. We view the final estimate involving regional averages as overly conservative on account of ignoring within-season independence amongst different parts of the Midwest, but include it to illustrate how the associated reduction in spatial degrees of freedom influences the results (*SI Appendix*, Table S3).

All regional trends that aggregate individual county trends reported in the work are computed as a weighted average according to average area planted. Individual country areas are computed as the average planted area across years.

ACKNOWLEDGMENTS. E.E.B. was supported by Packard Foundation Award 2009-34709; P.H. was supported by National Science Foundation Award 1521210; and N.D.M. was supported by USDA Grant 2016-67012-25208.

1. Evans LT (1993) *Crop Evolution, Adaptation, and Yield* (Cambridge Univ Press, Cambridge, UK).
2. Tilman D, Balzer C, Hill J, Befort BL (2011) Global food demand and the sustainable intensification of agriculture. *Proc Natl Acad Sci USA* 108:20260–20264.
3. Ray DK, Mueller ND, West PC, Foley JA (2013) Yield trends are insufficient to double global crop production by 2050. *PLoS One* 8:e66428.
4. Rosenzweig C, et al. (2013) Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc Natl Acad Sci USA* 111:3268–3273.
5. Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323:240–244.
6. Myers S, et al. (2017) Climate change and global food systems: Potential impacts on food security and undernutrition. *Annu Rev Public Health* 38:259–277.
7. Schlenker W, Roberts MJ (2009) Nonlinear temperature effects indicate severe damage to U.S. crop yields under climate change. *Proc Natl Acad Sci USA* 106:15594–15598.
8. Butler EE, Huybers P (2013) Adaptation of US maize to temperature variations. *Nat Clim Change* 3:68–72.
9. Kucharik CJ, Serbin SP (2008) Impacts of recent climate change on Wisconsin corn and soybean yield trends. *Environ Res Lett* 3:034003.
10. Lobell DB, Asner GP (2003) Climate and management contributions to recent trends in U.S. agricultural yields. *Science* 299:1032.
11. Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. *Science* 333:616–620.
12. Carlson RE (1990) Heat stress, plant-available soil moisture, and corn yields in Iowa: A short- and long-term view. *J Prod Agric* 3:293–297.
13. McKinnon KA, Rhines A, Tingley MP, Huybers P (2016) The changing shape of Northern Hemisphere summer temperature distributions. *J Geophys Res Atmos* 121:8849–8868.
14. Rhines A, McKinnon KA, Martin PT, Huybers P (2017) Seasonally resolved distributional trends of North American temperatures show contraction of winter variability. *J Clim* 30:1139–1157.
15. Mueller ND, et al. (2016) Cooling of US Midwest summer temperature extremes from cropland intensification. *Nat Clim Change* 6:317–322.
16. Kucharik CJ (2006) A multidecadal trend of earlier corn planting in the Central USA. *Agron J* 98:1544–1550.
17. Kucharik CJ (2008) Contribution of planting date trends to increased maize yields in the Central United States. *Agron J* 100:328–336.
18. Sacks WJ, Kucharik CJ (2011) Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. *Agric For Meteorol* 151:882–894.
19. Zhu P, et al. (2018) The important but weakening maize yield benefit of grain filling prolongation in the US Midwest. *Glob Change Biol* 24:4718–4730.
20. Burke M, Emerick K (2016) Adaptation to climate change: Evidence from US agriculture. *Am Econ J Econ Pol* 8:106–140.
21. Butler EE, Huybers P (2015) Variations in the sensitivity of US maize yield to extreme temperatures by region and growth phase. *Environ Res Lett* 10:034009.
22. Annan F, Schlenker W (2015) Federal crop insurance and the disincentive to adapt to extreme heat. *Am Econ Rev Pap Proc* 105:262–266.
23. Lobell DB, Bänziger M, Magorokosho C, Vivek B (2011) Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nat Clim Change* 1:42–45.
24. Rattalino Edreira JI, Otegui ME (2012) Heat stress in temperate and tropical maize hybrids: Differences in crop growth biomass partitioning and reserves use. *Field Crops Res* 130:97–98.
25. Sánchez B, Rasmussen A, Porter JR (2014) Temperature and the growth and development of maize and rice: A review. *Glob Change Biol* 20:408–417.
26. Ross EA, Douglas HC, Winter JM, Eltahir EAB (2018) Twentieth century regional climate change during the summer in the Central United States attributed to agricultural intensification. *Geophys Res Lett* 45:1586–1594.
27. Betts AK, Desjardins R, Worth D, Cerkowniak D (2013) Impact of land use change on the diurnal cycle climate of the Canadian prairies. *J Geophys Res Atmos* 118:11996–12011.
28. Zhao N, Han S, Xu D, Wang J, Yu H (2016) Cooling and wetting effects of agricultural development on near-surface atmosphere over Northeast China. *Adv Meteorol* 2016:6439276.
29. Mueller ND, et al. (2017) Global relationships between cropland intensification and summer temperature extremes over the last 50 years. *J Clim* 30:7505–7528.
30. Bonfils C, Lobell D (2007) Empirical evidence for a recent slowdown in irrigation-induced cooling. *Proc Natl Acad Sci USA* 104:13582–13587.
31. Lobell DB, et al. (2008) Irrigation cooling effect on temperature and heat index extremes. *Geophys Res Lett* 35:L09705.
32. Abendroth LJ, Elmore RW, Boyer MJ, Marlay MJ (2011) *Corn Growth and Development* (Iowa State Univ Extension, Ames, IA), PMR 1009.
33. Lauer J (2001) Earlier planting dates for corn: Real progress or an effect of global warming. *Wis Crop Manager* 8:83–85.
34. Gesch RW, Archer DW (2005) Influence of sowing date on emergence characteristics of maize seed coated with a temperature-activated polymer. *Agron J* 97:1543–1550.
35. Lobell DB (2014) Climate change adaptation in crop production: Beware of illusions. *Glob Food Secur.* 3:72–76.
36. Liu Z, Hubbard KG, Lin X, Yang X (2013) Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. *Glob Change Biol* 19:3481–3492.
37. Parmesan C, Gary Y (2003) A global coherent fingerprint of climate change impacts across natural systems. *Nature* 421:37–42.
38. Miller-Rushing AJ, Primack RB (2008) Global warming and flowering times in Thoreau's Concord: A community perspective. *Ecology* 89:332–341.
39. Ellwood ER, Temple SA, Primack RB, Bradley NL, Davis CC (2013) Record-breaking early flowering in the Eastern United States. *PLoS One* 8:e53788.
40. Bradley NL, Carl Leopold A, Ross J, Huffaker W (1999) Phenological changes reflect climate change in Wisconsin. *Proc Natl Acad Sci USA* 96:9701–9704.
41. Cassman KG, Dobermann A, Walters DT, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. *Annu Rev Environ Resour* 28:315–358.
42. Ray DK, Ramankutty N, Mueller ND, West PC, Foley J (2012) Recent patterns of crop yield growth and stagnation. *Nat Commun* 3:1293.
43. Grassini P, Eskridge KM, Cassman KG (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. *Nat Commun* 4:2918.
44. Leakey ADB, et al. (2009) Elevated CO2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *J Exp Bot* 60:2859–2876.
45. Long SP, Ainsworth EA, Leakey ADB, Nösberger J, Ort DR (2006) Food for thought: Lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science* 312:1918–1921.
46. Porter JR, et al. (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, chapter Food Security and Food Production Systems (Cambridge Univ Press, Cambridge, UK) pp 485–533.
47. Ainsworth EA, McGrath JM (2010) *Direct Effects of Rising Atmospheric Carbon Dioxide and Ozone on Crop Yields* (Springer, Dordrecht, The Netherlands), pp 109–130.
48. Tollenaar M, Fridgen J, Tyagi P, Stackhouse PW, Jr, Kumudini S (2017) The contribution of solar brightening to the US maize yield trend. *Nature Clim. Change* 7:275–278.
49. Natural Agricultural Statistics Service, US Department of Agriculture (2014) Quick stats 2.0. Retrieved from quickstats.nass.usda.gov/. Accessed March 22, 2018.
50. Menne MJ, Jr, Williams CN, United RSV (2014) States historical climatology network daily temperature, precipitation, and snow data.(Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN), Technical report.
51. Barber CB, Dobkin DP, Huhdanpaa HT (1996) The Quickhull algorithm for convex hulls. *ACM Trans Math Softw* 22:469–483.
52. Cornes RC, Jones PD (2013) How well does the era-interim reanalysis replicate trends in extremes of surface temperature across Europe? *J Geophys Res* 118:262–276.
53. Troy TJ, Kipgen C, Pal I (2015) The impact of climate extremes and irrigation on US crop yields. *Environ Res Lett* 10:054013.
54. Lauer J (2005) Optimum relative maturity for yield and profitability in corn. *Agron Advice* 28:39.
55. Diffenbaugh NS, Hertel TW, Scherer M, Verma M (2012) Response of corn markets to climate volatility under alternative energy futures. *Nat Clim Change* 2:514–518.
56. Tigchelaar M, Battisti DS, Naylor RL, Ray DK (2018) Future warming increases global maize yield variability with implications for food security. *Proc Natl Acad Sci USA* 115:6644–6649.
57. Huybers P, McKinnon KA, Rhines A, Tingley M (2014) U.S. daily temperatures: The meaning of extremes in the context of non-normality. *J Clim* 27:7368–7384.